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# Neutrino mass matrix with two zeros and leptogenesis

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## Abstract

The leptogenesis is studied in the neutrino mass matrix with two zeros, which reduces the number of independent phases of the CP violation. These texture zeros are decomposed into the Dirac neutrino mass matrix and the right-handed Majorana one in the see-saw mechanism. It is found that there are six textures for the Dirac neutrino mass matrix, among which one texture with three zeros has three phases, three textures with four zeros have two phases, and two textures with five zeros have only one phase in the basis with the real right-handed Majorana mass matrix. The relation between the leptogenesis and the low energy CP violation is discussed in typical textures. It is remarked that the leptogenesis is linked strongly with the CP violation in the neutrino oscillations. The predicted baryon asymmetry of the universe is consistent with the observed value.

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The Super-Kamiokande has almost confirmed the neutrino oscillation in the atmospheric neutrinos, which favors the  $\nu_\mu \rightarrow \nu_\tau$  process [1]. For the solar neutrinos [2,3], the recent data of the Super-Kamiokande and the Sudbury Neutrino Observatory also favor strongly the neutrino oscillation  $\nu_e \rightarrow \nu_{\mu,\tau}$  with the large mixing angle (LMA) MSW solution [4,5]. These results indicate the neutrino masses and mixings [6], especially, the bi-large flavor mixing. It is, therefore, possible to investigate the textures of the neutrino mass matrix.

Recently, Frampton et al. [7] found seven acceptable textures of the neutrino mass matrix with two independent vanishing entries in the basis with the diagonal charged lepton mass matrix. The further studies of these textures were presented by some authors [8–11]. Another insight has been also given focusing on texture zeros [12]. Since these textures are given for the light left-handed neutrinos, one needs to find the see-saw realization [13] of these textures from the standpoint of the model building. We have found the Dirac neutrino mass matrices and the right-handed Majorana neutrino ones, which give those seven textures [11].

These textures should be tested in the future experiments. We have already shown that they can be tested in the lepton flavor violating processes, especially,  $\mu \rightarrow e\gamma$  [11]. In order to search another test of them, we discuss the leptogenesis in this Letter. We study the relation between the leptogenesis and the low energy CP violation in these textures. We also predict the magnitude of the baryon asymmetry of the universe.

The leptogenesis [14] is an interesting mechanism to explain the observed baryon asymmetry of the universe. Since the leptogenesis depends strongly on the texture and the CP violating phases of the neutrino mass matrix, it

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is expected that the leptogenesis links with the low energy neutrino phenomena, especially the low energy CP violation in the neutrino oscillations [15–17]. The CP violation required for the leptogenesis stems from the CP violating phases in the right-handed sector, whereas the CP violation in the neutrino oscillations [18] can be described by the left-handed neutrino mixing matrix. In general, the independent CP violating phases are six for three generations and without a left-handed Majorana mass term, and therefore it is very difficult to find links between the leptogenesis and the low energy CP violation. Reduction of the number of phases has been done by considering the two right-handed neutrinos [19,20]. The interesting connection between the leptogenesis and the low energy CP violation has been presented in those works. It is remarked that there is one massless neutrino in this scheme.

In order to reduce the number of phases, we propose another approach, which is the texture zeros with the three right-handed neutrinos, being originated from the work by Frampton et al. [7]. We show that the low energy leptonic CP violation can be affected by the CP violating phases responsible for the leptogenesis in these texture zeros.

Let us discuss the structure of the CP violating phases in the neutrino mass matrix. There are seven acceptable textures with two independent zeros for the effective neutrino mass matrix  $M_\nu$  [7]. The two textures ( $A_1$  and  $A_2$ ) correspond to the hierarchical neutrino mass spectrum while others ( $B_1 \sim B_4$  and C) correspond to the quasi-degenerate neutrino mass spectrum. In this Letter, we concentrate only the hierarchical case of the textures  $A_1$  and  $A_2$ :

$$A_1: M_\nu = \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad A_2: M_\nu = \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}, \quad (1)$$

where the charged lepton mass matrix is the diagonal one. Since the component  $M_\nu(1, 1)$  is zero in these textures, the amplitude for the neutrinoless double beta decay vanishes to lowest order in neutrino masses.

In principle, these textures are given at the low energy scale because the experimental data are put to determine zeros, however, the structure of zeros in the mass matrix is not changed by the one-loop renormalization group equations [21]. Therefore, we discuss the see-saw realization in these textures at the right-handed Majorana neutrino mass scale:

$$\mathbf{M}_\nu = \mathbf{m}_D \mathbf{M}_R^{-1} \mathbf{m}_D^T, \quad (2)$$

where  $\mathbf{m}_D$  and  $\mathbf{M}_R$  are the Dirac neutrino mass matrix and the right-handed Majorana neutrino one, respectively. As far as we exclude the possibility that zeros are originated from cancellations among coefficients in the see-saw mechanism, the see-saw realization of these seven textures are not trivial. Then, these zeros should come from zeros of the Dirac neutrino mass matrix and the right-handed Majorana neutrino one. These results are summarized in Ref. [11].

Once the right-handed Majorana neutrino mass matrix is specified, the Dirac neutrino ones are selected in order to reproduce the textures in Eq. (1). The simplest right-handed Majorana neutrino mass matrix is the diagonal one, but there is no solution to give desirable texture zeros unless we consider cancellations between matrix elements of the Dirac and Majorana ones. Therefore, we take a following texture for the right-handed Majorana neutrinos

$$\mathbf{M}_R = \begin{pmatrix} 0 & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}, \quad (3)$$

where  $\times$ 's denote non-zero entries. It should be noted that specifying the texture of the right-handed Majorana neutrinos is a choice of weak basis. Furthermore we can take the matrix in Eq. (3) to be real. Then, the CP violating phases appear only in the Dirac neutrino mass matrix. In this case, we have six Dirac neutrino mass matrices, which

reproduce the texture  $A_1$  in Eq. (1):

$$\mathbf{m}_D = \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \mathbf{0} & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \times & \mathbf{0} \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \mathbf{0} & \mathbf{0} \end{pmatrix}, \quad (4)$$

and

$$\mathbf{m}_D = \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \times \\ \times & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \times \\ \times & \mathbf{0} & \times \end{pmatrix}, \quad (5)$$

where  $\times$ 's denote complex numbers. As seen later the textures in Eq. (5) give different predictions from the ones in Eq. (4) for the decay rate of  $\mu \rightarrow e\gamma$ .

For the texture  $A_2$  in Eq. (1), we obtain

$$\mathbf{m}_D = \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \times \\ \mathbf{0} & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \times \\ \mathbf{0} & \mathbf{0} & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \end{pmatrix}, \quad (6)$$

and

$$\mathbf{m}_D = \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \mathbf{0} & \times \\ \mathbf{0} & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \mathbf{0} & \times \\ \mathbf{0} & \mathbf{0} & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \times & \times \end{pmatrix}. \quad (7)$$

The textures in Eq. (7) also give different predictions from the ones in Eq. (6) for  $\mu \rightarrow e\gamma$ .

Although there are phases in all non-zero entries, those phases are not necessarily physical quantities. Actually, three phases are removed by the re-definition of the left-handed neutrino fields. There is no freedom of the re-definition for the right-handed ones in the basis with real  $M_R$ . As seen in Eqs. (4)–(7), the number of independent phases are classified as: one texture of three zeros with three phases, three textures of four zeros with two phases and two textures of five zeros with one phase. Thus, we get the reduction of the number of phases in our textures while there are six independent phases in the neutrino mass matrix without zeros.

What kind of experiments can test these textures? It is well-known that the Yukawa coupling of the neutrino contributes to the lepton flavor violation (LFV). Many authors have studied the LFV in the minimal supersymmetric standard model (MSSM) with right-handed neutrinos assuming the relevant neutrino mass matrix [22–27]. In the MSSM with soft breaking terms, there exist lepton flavor violating terms such as off-diagonal elements of slepton mass matrices and trilinear couplings (A-term). It is noticed that large neutrino Yukawa couplings and large lepton mixings generate the large LFV in the left-handed slepton masses. For example, the decay rate of  $\mu \rightarrow e\gamma$  can be approximated as follows:

$$\Gamma(\mu \rightarrow e\gamma) \simeq \frac{e^2}{16\pi} m_\mu^5 F \left| \frac{(6 + 2a_0^2)m_{S0}^2}{16\pi^2} (\mathbf{Y}_\nu \mathbf{Y}_\nu^\dagger)_{21} \ln \frac{M_X}{M_R} \right|^2, \quad (8)$$

where the neutrino Yukawa coupling matrix  $\mathbf{Y}_\nu$  is given as  $\mathbf{Y}_\nu = \mathbf{m}_D/v_2$  ( $v_2$  is a VEV of Higgs) at the right-handed mass scale  $M_R$ , and  $F$  is a function of masses and mixings for SUSY particles. In Eq. (8), we assume the universal scalar mass ( $m_{S0}$ ) for all scalars and the universal A-term ( $A_f = a_0 m_{S0} Y_f$ ) at the GUT scale  $M_X$ . Therefore, the branching ratio  $\mu \rightarrow e\gamma$  depends considerably on the texture of the Dirac neutrino [25–27].

The magnitude of  $(\mathbf{m}_D \mathbf{m}_D^\dagger)_{21}$  is important to predict the branching ratio of  $\mu \rightarrow e\gamma$ .<sup>1</sup> Many works have shown that this branching ratio is too large [25,26]. However, zeros in the Dirac neutrino mass matrix may lead to  $(\mathbf{m}_D \mathbf{m}_D^\dagger)_{21} = 0$ , and then it suppress the  $\mu \rightarrow e\gamma$  decay. The branching ratio is safely predicted to be below

<sup>1</sup> Although the right-handed Majorana neutrino mass matrix is not a diagonal one in our case,  $\mathbf{m}_D \mathbf{m}_D^\dagger$  does not depend on the right-handed sector.

the present experimental upper bound  $1.2 \times 10^{-11}$  [28] due to zeros. Actually, the case of  $(\mathbf{m}_D \mathbf{m}_D^\dagger)_{21} = 0$  was examined carefully in Ref. [29]. We have several textures, which lead to  $(\mathbf{m}_D \mathbf{m}_D^\dagger)_{21} = 0$  as seen in Eqs. (5) and (7). Therefore, we examine the textures of the Dirac neutrinos in Eqs. (5) and (7) for the leptogenesis in the following.

At first, let us discuss the texture in the  $A_1$  case in Eq. (1). Key ingredients are the structure of CP violating phases and the magnitudes of each entry for the Dirac neutrino mass matrices in Eq. (5) since the right-handed Majorana neutrino mass matrix is taken to be real. Although the non-zero entries  $\times$  in the Dirac neutrino mass matrix are complex, three phases are removed by the re-definition of the left-handed neutrino fields. There is no freedom of re-definition for the right-handed ones in the basis with real  $\mathbf{M}_R$ . Furthermore, we move to the diagonal basis of the right-handed Majorana neutrino mass matrix in order to calculate the magnitude of the leptogenesis. Then, the Dirac neutrino mass matrices  $\bar{\mathbf{m}}_D$  in the new basis is given as follows:

$$\bar{\mathbf{m}}_D = \mathbf{P}_L \mathbf{m}_D \mathbf{O}_R, \quad (9)$$

where  $\mathbf{P}_L$  is a diagonal phase matrix and  $\mathbf{O}_R$  is the orthogonal matrix which diagonalizes  $\mathbf{M}_R$  as  $\mathbf{O}_R^T \mathbf{M}_R \mathbf{O}_R$  in Eq. (3). Since the phase matrix  $\mathbf{P}_L$  can remove one phase in each row of  $\mathbf{m}_D$ , three phases disappear in  $\bar{\mathbf{m}}_D$ .

By taking three eigenvalues of  $\mathbf{M}_R$  as follows:<sup>2</sup>

$$M_1 = -\lambda^m M_0, \quad M_2 = \lambda^n M_0, \quad M_3 = M_0, \quad (10)$$

where  $\lambda \simeq 0.22$ , we obtain the orthogonal matrix  $\mathbf{O}_R$  as

$$\mathbf{O}_R = \begin{pmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \tan^2 \theta = \lambda^{m-n}. \quad (11)$$

We take  $m = 4, n = 2$  as a typical case in order to find links between the leptogenesis and the low energy CP violation. The magnitude of each entry in  $M_\nu$  ( $A_1$ ) is given to be consistent with the experimental data as follows:

$$M_\nu = m_0 \begin{pmatrix} 0 & 0 & \lambda \\ 0 & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}, \quad (12)$$

where  $m_0 \simeq \sqrt{\Delta m_{\text{atm}}^2}/2$  with  $\Delta m_{\text{atm}}^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2$  is taken. Then two mass matrices  $\mathbf{m}_D$  in Eq. (5) can be parametrized in the new basis as follows:

$$\bar{\mathbf{m}}_D = m_{D0} \begin{pmatrix} 0 & a\lambda^2 & 0 \\ 0 & 0 & b \\ c\lambda^2 e^{i\rho} & d\lambda^k e^{i\sigma} & f \end{pmatrix} \mathbf{O}_R, \quad (k \geq 1) \quad (\text{A11}), \quad m_{D0} \begin{pmatrix} 0 & a\lambda^2 & 0 \\ 0 & 0 & b \\ c\lambda^2 e^{i\rho} & 0 & f \end{pmatrix} \mathbf{O}_R, \quad (\text{A12}), \quad (13)$$

where  $k$  is a positive integer with  $k \geq 1$ , and  $a, b, c, d, f$  are real and order one coefficients. The magnitude of  $m_{D0}$  is determined by the relation  $m_{D0}^2 \simeq m_0 M_0$ . There are two independent phases in (A11), but only one phase in (A12) as seen in Eq. (13). The texture in (A12) corresponds to the  $d = 0$  limit in (A11).

In the limit  $M_1 \ll M_2, M_3$ , the lepton number asymmetry (CP asymmetry) for the lightest heavy Majorana neutrino ( $N_1$ ) decays into  $l^\mp \phi^\pm$  [30] is given by

$$\epsilon_1 = \frac{\Gamma_1 - \bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} \simeq -\frac{3}{16\pi v^2} \left( \frac{\text{Im}[(\bar{m}_D^\dagger \bar{m}_D)_{12}]^2}{(\bar{m}_D^\dagger \bar{m}_D)_{11}} \frac{M_1}{M_2} + \frac{\text{Im}[(\bar{m}_D^\dagger \bar{m}_D)_{13}]^2}{(\bar{m}_D^\dagger \bar{m}_D)_{11}} \frac{M_1}{M_3} \right), \quad (14)$$

<sup>2</sup> The minus sign of  $M_1$  is necessary to reproduce  $\mathbf{M}_R$  in Eq. (3). This minus sign is transferred to  $\mathbf{m}_D$  by the right-handed diagonal phase matrix  $\text{diag}(i, 1, 1)$ .

where  $v = 174$  GeV. The lepton asymmetry  $Y_L$  is related to the CP asymmetry through the relation

$$Y_L = \frac{n_L - n_{\bar{L}}}{s} = \kappa \frac{\epsilon_1}{g_*}, \quad (15)$$

where  $s$  denotes the entropy density,  $g_*$  is the effective number of relativistic degrees of freedom contributing to the entropy and  $\kappa$  is the so-called dilution factor which accounts for the washout processes (inverse decay and lepton number violating scattering). In the case of the standard model (SM), one gets  $g_* = 106.75$ .

The produced lepton asymmetry  $Y_L$  is converted into a net baryon asymmetry  $Y_B$  through the  $(B + L)$ -violating sphaleron processes. One finds the relation [31]

$$Y_B = \xi Y_{B-L} = \frac{\xi}{\xi - 1} Y_L, \quad \xi = \frac{8N_f + 4N_H}{22N_f + 13N_H}, \quad (16)$$

where  $N_f$  and  $N_H$  are the number of fermion families and complex Higgs doublets, respectively. Taking into account  $N_f = 3$  and  $N_H = 1$  in the SM, we get

$$Y_B \simeq -\frac{28}{51} Y_L. \quad (17)$$

On the other hand, the low energy CP violation, which is a measurable quantity in the long baseline neutrino oscillations [18], is given by the Jarlskog determinant  $J$  [32], which is calculated by

$$\det[\mathbf{M}_\ell \mathbf{M}_\ell^\dagger, \mathbf{M}_\nu \mathbf{M}_\nu^\dagger] = -2i J (m_\tau^2 - m_\mu^2)(m_\mu^2 - m_e^2)(m_e^2 - m_\tau^2)(m_3^2 - m_2^2)(m_2^2 - m_1^2)(m_1^2 - m_3^2), \quad (18)$$

where  $\mathbf{M}_\ell$  is the diagonal charged lepton mass matrix, and  $m_1, m_2, m_3$  are neutrino masses.

It is very interesting to investigate links between the leptogenesis ( $\epsilon_1$ ) and the low energy CP violation ( $J$ ) in the textures of Eq. (13). In the texture (A11),  $\epsilon_1$  and  $J$  are given as

$$\begin{aligned} \epsilon_1 \simeq & -\frac{3m_{D0}^2}{16\pi v^2} \left[ d^2 \lambda^{2(k+1)} \frac{c^2 \sin 2(\rho - \sigma) - 2cd\lambda^{k-1} \sin(\rho - \sigma)}{c^2 + d^2 \lambda^{2(k-1)} - 2cd\lambda^{k-1} \cos(\rho - \sigma)} \right. \\ & \left. + f^2 \lambda^4 \frac{c^2 \sin 2\rho + d^2 \lambda^{2(k-1)} \sin 2\sigma - 2cd\lambda^{k-1} \sin(\rho + \sigma)}{c^2 + d^2 \lambda^{2(k-1)} - 2cd\lambda^{k-1} \cos(\rho - \sigma)} \right] \quad (k \geq 1), \\ J \simeq & \frac{1}{64} a^2 b^4 c^3 f^2 \lambda^2 [c \sin 2\rho - 2d\lambda^{k-1} \sin(\rho + \sigma)] \frac{\Delta m_{\text{atm}}^2}{\Delta m_{\text{sol}}^2}, \end{aligned} \quad (19)$$

respectively. Both  $\epsilon_1$  and  $J$  are given in terms of two phases  $\rho$  and  $\sigma$ . However, the dominant terms are given by phase  $\rho$  as far as  $k \geq 2$ . It is remarked that the leptogenesis is linked strongly with the CP violation in the neutrino oscillations. The relative sign of  $\epsilon_1$  and  $J$  is opposite in this case. The case of  $k = 1$  is exceptional one. Detailed numerical study will be needed in  $k = 1$  because both  $\epsilon_1$  and  $J$  depend on parameters  $c, d, \rho$  and  $\sigma$ .

The case of the texture (A12) is clear because there is only one phase  $\rho$ . In this case,  $\epsilon_1$  and  $J$  are given in the  $d = 0$  limit of the texture (A11) as follows:

$$\epsilon_1 \simeq -\frac{3m_{D0}^2}{16\pi v^2} f^2 \lambda^4 \sin 2\rho, \quad J \simeq \frac{1}{64} a^2 b^4 c^4 f^2 \lambda^2 \frac{\Delta m_{\text{atm}}^2}{\Delta m_{\text{sol}}^2} \sin 2\rho. \quad (20)$$

The relative sign of  $\epsilon_1$  and  $J$  is also opposite. It may be helpful to note that only the second term in the right-handed side of Eq. (14) contributes to  $\epsilon_1$  since  $\text{Im}[\{(\bar{m}_D^\dagger \bar{m}_D)_{12}\}^2]$  vanishes.

On the other hand, taking the LMA-MSW solution  $\Delta m_{\text{sol}}^2 / \Delta m_{\text{atm}}^2 = \lambda^3 \sim \lambda^2$  and  $\sin 2\rho \simeq 1$ , we predict  $J \simeq 0.01$ , which is rather large and then is favored for the experimental measurement.

Next, consider the case  $A_2$  for  $M_\nu$ . Since the magnitude of each entry in  $M_\nu$  is given to be consistent with the experimental data as follows:

$$M_\nu = m_0 \begin{pmatrix} 0 & \lambda & 0 \\ \lambda & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}, \quad (21)$$

three mass matrices  $\mathbf{m}_D$  in Eq. (7) can be parametrized in the new basis as follows:

$$\bar{\mathbf{m}}_D = m_{D0} \begin{pmatrix} 0 & a\lambda^2 & 0 \\ b\lambda^2 & 0 & ce^{i\rho} \\ 0 & d\lambda^p e^{i\sigma} & f \end{pmatrix} O_R, \quad (\text{A21}),$$

$$m_{D0} \begin{pmatrix} 0 & a\lambda^2 & 0 \\ b\lambda^2 & 0 & c\lambda^q e^{i\rho} \\ 0 & d\lambda e^{i\sigma} & f \end{pmatrix} O_R, \quad (\text{A22}), \quad (22)$$

where  $p \geq 1$  and  $q \geq 0$ , and

$$\bar{\mathbf{m}}_D = m_{D0} \begin{pmatrix} 0 & a\lambda^2 & 0 \\ b\lambda^2 & 0 & ce^{i\rho} \\ 0 & 0 & f \end{pmatrix} O_R, \quad (\text{A23}),$$

$$m_{D0} \begin{pmatrix} 0 & a\lambda^2 & 0 \\ b\lambda^2 & 0 & 0 \\ 0 & d\lambda e^{i\sigma} & f \end{pmatrix} O_R, \quad (\text{A24}). \quad (23)$$

The textures in (A23) and (A24) correspond to the  $d = 0$  and  $c = 0$  limits of (A21) and (A22) in Eq. (22), respectively.

For the texture (A21)  $\epsilon_1$  and  $J$  are given as

$$\begin{aligned} \epsilon_1 &\simeq \frac{3m_{D0}^2}{16\pi v^2} \frac{1}{b^2 + d^2\lambda^{2(p-1)}} \lambda^4 [b^2 c^2 \sin 2\rho - d^2 f^2 \lambda^{2(p-1)} \sin 2\sigma - 2bcd f \lambda^{p-1} \sin(\rho - \sigma)] \quad (p \geq 1), \\ J &\simeq \frac{1}{64} a^2 b^3 f^2 \lambda^2 \frac{\Delta m_{\text{atm}}^2}{\Delta m_{\text{sol}}^2} [bc^2 f^2 \sin 2\rho + d\lambda^{p-1} \{2c^3 f \sin(\rho - \sigma) + bc^2 d\lambda^{p-1} \sin 2(\rho - \sigma) \\ &\quad + b^3 d\lambda^{p-1} \sin 2\sigma + 2b^2 c f \sin(\rho + \sigma)\}], \end{aligned} \quad (24)$$

and for the texture (A22)  $\epsilon_1$  and  $J$  are given as

$$\begin{aligned} \epsilon_1 &\simeq \frac{3m_{D0}^2}{16\pi v^2} \frac{1}{b^2 + d^2} \lambda^4 [b^2 c^2 \lambda^{2q} \sin 2\rho - d^2 f^2 \sin 2\sigma - 2bcd f \lambda^q \sin(\rho - \sigma)] \quad (q \geq 0), \\ J &\simeq \frac{1}{64} a^2 b^3 f^2 \lambda^2 \frac{\Delta m_{\text{atm}}^2}{\Delta m_{\text{sol}}^2} [b^3 d^2 \sin 2\sigma + c\lambda^q \{2c^2 d f \lambda^{2q} \sin(\rho - \sigma) + bc d^2 \lambda^q \sin 2(\rho - \sigma) + bc f^2 \lambda^q \sin 2\rho \\ &\quad + 2b^2 d f \sin(\rho + \sigma)\}]. \end{aligned} \quad (25)$$

Both  $\epsilon_1$  and  $J$  are dominated by one phase as far as  $p \geq 2$  and  $q \geq 1$ . Therefore, the leptogenesis is linked strongly with the CP violation in the neutrino oscillations except for the case of  $p = 1$  and  $q = 0$ .

In the case of the textures (A23) and (A24),  $\epsilon_1$  and  $J$  are given by putting  $d = 0$  and  $c = 0$  in Eqs. (24) and (25), respectively. Therefore  $\epsilon_1$  and  $J$  are simply given as

$$\epsilon_1 \simeq \frac{3m_{D0}^2}{16\pi v^2} c^2 \lambda^4 \sin 2\rho, \quad J \simeq \frac{1}{64} a^2 b^4 c^2 f^4 \lambda^2 \frac{\Delta m_{\text{atm}}^2}{\Delta m_{\text{sol}}^2} \sin 2\rho, \quad (26)$$

for (A23), and

$$\begin{aligned}\epsilon_1 &\simeq -\frac{3m_{D0}^2}{16\pi v^2} \frac{d^2 f^2}{b^2 + d^2} \lambda^4 \sin 2\sigma, \\ J &\simeq \frac{1}{64} a^2 b^6 d^2 f^2 \lambda^2 \frac{\Delta m_{\text{atm}}^2}{\Delta m_{\text{sol}}^2} \sin 2\sigma,\end{aligned}\quad (27)$$

for (A24), respectively. The relative sign of  $\epsilon_1$  and  $J$  is same for (A23) while opposite for (A24) as seen in Eqs. (26) and (27). Therefore, these textures are testable in the future.

In order to calculate the baryon asymmetry, we need the dilution factor involves the integration of the full set of Boltzmann equations [33]. A simple approximated solution which has been frequently used is given by [34]

$$\kappa = \frac{0.3}{K_R} (\ln K_R)^{-0.6} \quad (10 \leq K_R \leq 10^6), \quad (28)$$

where the parameter  $K_R$  is defined as the ratio of the thermal average of the  $N_1$  decay rate and the Hubble parameter at the temperature  $T = M_1$ ,

$$K_R = \frac{M_P}{1.7 \times 8\pi v^2 \sqrt{g_*}} \frac{(\bar{m}_D^\dagger \bar{m}_D)_{11}}{M_1}, \quad (29)$$

where  $M_P \simeq 1.22 \times 10^{19}$  GeV is the Planck mass. The value of  $K_R$  is approximately  $\sim 23$ , which is independent of  $M_1$ , in our textures. Therefore, the dilution factor is not so suppressed.

By using this approximate dilution factor, we have calculated  $Y_B$  in our textures. Since  $\epsilon_1 \simeq \lambda^4$  in all cases of our textures, we calculate  $Y_B$  for the case of (A12) with  $f = 1$  in Eq. (20) as a typical one. Our numerical result is shown in Fig. 1. As seen in Fig. 1, the predicted  $Y_B$  is consistent with the observed value  $Y_B = (1.7 \sim 8.1) \times 10^{-11}$  for  $M_0 = 10^{13} \sim 10^{14}$  GeV and  $\sin 2\rho = 0.2 \sim 1$ . More detailed analyses will be given elsewhere. Thus, our textures of the Dirac neutrinos is favored in the scenario of the leptogenesis.

The discussion and summary are given as follows.

We have studied the leptogenesis in the neutrino mass matrix with two zeros, which reduces the number of CP violating phases. After see-saw realization in the textures A<sub>1</sub> and A<sub>2</sub>, we have found that one texture with three zeros has three phases, three textures with four zeros have two phases and two textures with five zeros have only

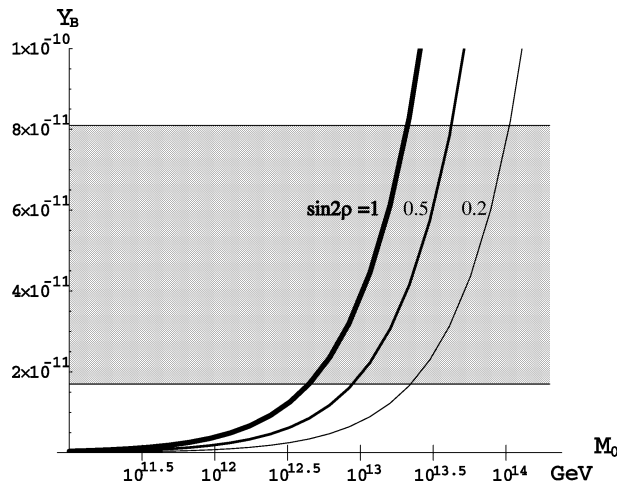


Fig. 1. Predicted  $Y_B$  vs.  $M_0$  for  $\sin 2\rho = 0.2, 0.5, 1$  in the texture (A12). The gray region is allowed by the observed baryon asymmetry.

one phase for the Dirac neutrino mass matrices, respectively. Taking a typical mass hierarchy of the right-handed Majorana neutrinos, we have calculated the relevant quantities for the leptogenesis and the low energy CP violation,  $\epsilon_1$  and  $J$ , respectively. The leptogenesis is linked strongly with the CP violation in the neutrino oscillations in our textures although there are a few exceptional cases. We have also given the prediction  $Y_B$ , which is consistent with the observed value. We will present more systematic and detailed analyses elsewhere. In order to test the link between the leptogenesis and the low energy CP violation, we expect that the measurement of the CP violation in the experiments of the long baseline neutrino oscillations.

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